Remote Sensing Monitoring of Eco-environmental Impacts of Hydropower Station Construction and Operation in Arid Regions: A Postprint

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Abstract

Hydropower represents a crucial clean energy source in China; however, the protracted construction and operational cycles of hydropower stations render their long-term impacts on ecosystems uncertain. This is particularly pronounced in arid regions, where unique geographical locations and dry, precipitation-deficient climatic conditions result in diminished ecosystem self-regulation capacity, making damaged local ecological environments often irreparable. This study examines the Longyangxia Hydropower Station—a representative facility in China' s arid zone—by employing Landsat satellite data and terrestrial remote sensing products, and applying methodologies including buffer analysis and trend analysis to monitor the ecological environment surrounding the station from 2000 to 2021 and assess its influence on the adjacent regional ecosystem. The findings indicate: (1) The land use pattern around Longyangxia Hydropower Station remained substantially unchanged during 2000–2021, with a modest increase in the relative proportion of grassland area and a slight decrease in other land use categories. (2) Wetland area in the vicinity of Longyangxia Hydropower Station exhibited significant expansion from 2000 to 2021. (3) Vegetation growth conditions in the station' s peripheral region have been favorable over the past two decades, with an increased areal proportion of high vegetation coverage zones. (4) The carbon sequestration capacity of vegetation in the surrounding area has enhanced, and vegetation productivity has gradually recovered as the growth rate of wetland area decelerated.

Full Text

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Remote Sensing Monitoring of Ecological Environment Impacts of Hydropower Station Construction and Operation in Arid Areas: A

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Case Study of Longyangxia Hydropower Station

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Abstract

Hydropower represents a crucial clean energy source in China. However, the extended construction and operational cycles of hydropower stations create uncertainty regarding their long-term ecosystem impacts. This uncertainty is particularly pronounced in arid regions, where unique geographical locations and dry, rain-scarce climatic conditions result in limited ecosystem self-regulation capacity, making environmental restoration exceptionally challenging following ecological damage. This study examines Longyangxia Hydropower Station as a representative case in China' s arid region, utilizing Landsat series satellite data and terrestrial remote sensing products. Through buffer zone analysis and trend analysis methods, we monitored the ecological environment surrounding the hydropower station from 2000 to 2021 and assessed its impacts on the surrounding regional ecosystem. The results demonstrate that: (1) The land use pattern around Longyangxia Hydropower Station remained largely unchanged from 2000 to 2021, with grassland proportion increasing slightly while other land use types decreased marginally. (2) The wetland area in the vicinity of the hydropower station increased significantly during this period. (3) Vegetation in the surrounding area exhibited robust growth, with the proportion of high vegetation coverage areas expanding. (4) Vegetation carbon sequestration capacity improved, and vegetation productivity gradually recovered as the wetland area growth rate decelerated.

Keywords: hydropower stations; ecological environment impact; vegetation coverage; land use types; remote sensing monitoring

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Introduction

To mitigate global climate change driven by anthropogenic CO_2 emissions, China has established a strategic goal to achieve carbon neutrality before 2060, with a primary initiative being the accelerated development of new energy industries including hydropower, solar, and wind generation to facilitate the transition from traditional to clean energy sources. Hydropower represents the most stable and reliable renewable energy source, yet its construction and operation inevitably impact surrounding ecological environments. Achieving synergy between hydropower development and ecological protection necessitates urgent monitoring and quantitative assessment of these environmental impacts. Remote sensing technology offers advantages of broad monitoring coverage, high information precision, and rapid data acquisition, providing objective and accurate data for ecological environment impact monitoring.

Numerous studies have employed remote sensing to monitor and evaluate ecological environments around hydropower stations. Previous research has examined vegetation coverage changes and soil erosion in the Ertan Reservoir catchment using multi-source remote sensing data, revealing improving soil loss conditions. Studies of the Lancang River' s Manwan Hydropower Station have applied remote sensing image processing to address challenges in vegetation cover surveys within canyon mountainous areas. Research on the Mekong River hydropower stations developed novel remote sensing methods using time series and annual Normalized Difference Vegetation Index (NDVI) composites combined with Digital Elevation Models (DEM) to determine dam construction timelines and assess impact distances on nearby land use and land cover. Other work has integrated Landsat and Synthetic Aperture Radar (SAR) data to monitor topographic, geological, and water level factors affecting hydropower stations, analyzing environmental impacts of Ethiopia' s Grand Renaissance Dam and Kenya' s Ewaso Nyiro Dam. Studies in the "Belt and Road" region have analyzed impacts of Chinese-aided hydropower projects on surrounding vegetation growth and ecological resources.

However, existing domestic research on hydropower station ecological impacts predominantly focuses on southern humid regions, with relatively few studies in northwestern arid and semi-arid areas. Arid regions, mostly located inland, feature fragile ecological environments with poor self-regulation capacity, where damage is difficult to repair. China has constructed and operates multiple large hydropower stations in arid and semi-arid regions, including Longyangxia, Gongboxia, and Jishixia stations, yet the long-term impacts of construction and operation on surrounding ecological environments remain unclear. This study addresses this gap by establishing a monitoring system and database for hydropower station ecological impacts in arid regions using Landsat satellite data and multiple terrestrial remote sensing products, with Longyangxia Hydropower Station as a case study to analyze impacts on surrounding ecological environments and provide scientific support for high-quality hydropower development and ecological protection in China.

1.1 Study Area Overview

Longyangxia Hydropower Station is located on the main stream of the Yellow River between Gonghe County and Guide County in Qinghai Province [Figure

1: see original paper]. The region features a plateau continental climate characterized by low, concentrated rainfall, long sunshine duration, and strong solar radiation. Reservoir water levels typically peak in October each year before gradually receding. Construction began in 1976, with the river closure completed in 1979 and all four generating units operational by October 1987. As a primary power plant in the Northwest China Grid, the station has a total installed capacity of 1,280 MW and an average annual generation of 5.942 billion kWh. Serving multiple purposes including power generation, irrigation, flood control, and ice jam prevention, it represents the first large-scale cascade hydropower station on the upper Yellow River mainstem, earning the designation of the "head" of Yellow River hydropower development.

1.2 Data Sources

This study utilized three main data types: Landsat remote sensing imagery, land use data, and vegetation productivity data. Landsat data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn/), including Landsat 5 TM data (30 m spatial resolution, 16-day revisit cycle) and Landsat 8 OLI data (30 m spatial resolution, 16-day revisit cycle). Land use data were derived from the Chinese Multi-period Land Use Remote Sensing Monitoring Dataset (CNLUCC), available from the Resource and Environmental Science Data Center (https://www.resdc.cn/). This dataset, based on Landsat TM imagery with manual visual interpretation, currently includes five periods. Vegetation productivity data included MOD17A3 Gross Primary Productivity (GPP) and Net Primary Productivity (NPP) products from USGS (https://lpdaac.usgs.gov/products/mod17a3hgfv061/), with 500 m spatial resolution, annual temporal resolution, and units of kg $C \cdot m^{-2} \cdot yr^{-1}$. Net Ecosystem Productivity (NEP) data were obtained from the National Earth System Science Data Center (http://www.geodata.cn/), with 500 m spatial resolution and annual temporal resolution.

1.3 Research Methods

1.3.1 Wetland Area Extraction Following China' s Wetland Protection Law definition, this study defined wetlands as natural or artificial waterlogged areas with significant ecological functions, including perennial or seasonal water zones. The wetland area in the Longyangxia reservoir region primarily comprises the reservoir itself. Using Landsat satellite data, we calculated the Normalized Difference Water Index (NDWI) proposed by McFeeters to extract water bodies and compute reservoir area. Due to missing remote sensing imagery for certain years, we performed linear interpolation for 2000-2021 data. The wetland area analyzed represents the average of multi-year values.

1.3.2 Buffer Zone Analysis Method Buffer zone analysis was employed to investigate vegetation growth conditions and land use changes around Longyangxia Reservoir, indicating ecological conditions and resource utilization within specific distances from the hydropower station. This common neighborhood analysis method uses specific points, lines, or areas as centers to establish buffer zones at set distances, forming buffer polygons that exclude interference from other information and expand spatial data in two-dimensional space. Previous research indicates that hydropower dams typically impact land use and land cover within buffer radii of 4.0 km upstream and 2.5 km downstream. Considering Longyangxia Reservoir' s boundaries and surrounding geography, this study established buffer zones extending 5 km outward from the reservoir edge.

1.3.3 Land Use Change Analysis The land use dataset includes six primary types: cultivated land, forestland, grassland, water bodies, residential land, and unused land, with 25 secondary types. As Longyangxia Reservoir surroundings contain limited land use types and minimal residential land, this study focused on five primary types: cultivated land, forestland, grassland, water bodies, and unused land. We analyzed changes in the proportion of each land use type during five periods and employed land use transfer matrices to reflect dynamic conversion information between land types during two time periods.

1.3.4 Vegetation Growth Status Inversion Key vegetation growth parameters include Normalized Difference Vegetation Index (NDVI) and Fractional Vegetation Cover (FVC). FVC represents the proportion of vegetation vertical projection area to the total study area, effectively reflecting vegetation change characteristics and ecological environment variations. This study calculated FVC using the dimidiate pixel model based on NDVI:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$

where $NDVI$ is the pixel value, $NDVI_{soil}$ is the NDVI value for bare soil, and $NDVI_{veg}$ is the NDVI value for full vegetation cover. Given difficulties in obtaining ground-measured FVC data for different natural vegetation types, we selected NDVI values at 5% and 95% cumulative frequency as $NDVI_{soil}$ and $NDVI_{veg}$, respectively.

Vegetation productivity was assessed using Gross Primary Productivity (GPP), Net Primary Productivity (NPP), and Net Ecosystem Productivity (NEP). GPP represents the total organic carbon fixed by green plants through photosynthesis per unit time and area, determining initial material and energy input to terrestrial ecosystems. NPP is the net organic dry matter accumulated by green plants per unit area and time, representing the portion of fixed organic carbon after respiration consumption for growth and reproduction. NEP indicates ecosystem net carbon flux, representing the carbon sink capacity of terrestrial ecosystems. The study' s technical roadmap is shown in [Figure 2: see original paper].

Results

2.1 Wetland Area Changes Around the Hydropower Station

Annual wetland area changes and trends for Longyangxia Reservoir from 2000 to 2021 are illustrated in [Figure 3: see original paper]. The minimum wetland area occurred in 2000 at 246.53 km^2, while the maximum reached 394.91 km^2 in 2021. Overall, reservoir wetland area increased with fluctuations, showing a significant upward trend ($P < 0.05$) with an increase of 5.66 km^2. The wetland area expansion trend around Longyangxia Hydropower Station indicates that construction and operation promote wetland protection.

2.2 Vegetation Growth Status Changes

2.2.1 Vegetation Coverage Changes Around the Hydropower Station To assess impacts of hydropower station construction and operation on regional vegetation coverage, we used NDVI values to invert FVC and classified it into six grades: 0%-10%, 10%-20%, 20%-40%, 40%-60%, 60%-80%, and 80%-100% to analyze changes over the past two decades.

Analysis of multi-year changes within the same coverage grade (Table 1) reveals that from 2000 to 2021, the area proportions of 0%-10%, 10%-20%, and 20%-40% FVC grades decreased significantly, with the 20%-40% grade showing the largest reduction at 2.46%. Conversely, 40%-60%, 60%-80%, and 80%-100% grades showed increasing trends, with the 60%-80% grade exhibiting the greatest increase at 1.71%.

Spatial distribution of FVC around Longyangxia Hydropower Station shows high coverage across most areas [Figure 4: see original paper]. Low FVC values (0-0.2) occur primarily in northeastern and southeastern portions, while northwestern vegetation coverage is lower than southern areas, with most regions ranging 0.4-0.6. High FVC areas (0.8-1.0) have continuously expanded, particularly in northwestern and southeastern regions.

Long-term trend analysis of different FVC grades [Figure 5: see original paper] indicates that 60%-80% and 80%-100% coverage areas show significant increasing trends of $0.25\% \cdot a^{-1}$ and $0.61\% \cdot a^{-1}$ ($P < 0.05$), respectively. Meanwhile, low coverage areas (0%-10%, 10%-20%, 20%-40%) show decreasing trends, with the 20%-40% grade decreasing most significantly at $-1.38\% \cdot a^{-1}$ ($P < 0.05$). Notably, different FVC grades show large fluctuations in later periods; for example, the 2021 vegetation growth rate approached that of 2020, likely related to low precipitation, indicating vegetation sensitivity to climate variability. Overall, during Longyangxia Hydropower Station' s construction and operation, vegetation coverage improved, with increasing proportions of high-coverage areas.

2.2.2 Analysis of Vegetation Growth Conditions Around Longyangxia Reservoir We used NDVI to represent overall vegetation growth conditions. After extracting wetland boundaries, buffer zone analysis revealed that the mean NDVI around the reservoir was lowest in 2001 at 0.29 and highest in 2020 at 0.58. Overall, reservoir peripheral NDVI showed a significant upward trend with an increase rate of $0.009 \cdot a^{-1}$ ($P < 0.05$), indicating improving vegetation growth conditions around Longyangxia Hydropower Station, particularly in northwestern and southeastern areas where vegetation changes were more pronounced [Figure 6: see original paper].

NDVI distribution analysis [Figure 7: see original paper] shows higher values in the eastern reservoir region, with some areas exceeding 0.6-0.8 and extensive high-coverage vegetation. Western areas show lower NDVI values, mostly below 0.2. The increasing NDVI trend demonstrates that vegetation growth conditions around Longyangxia Hydropower Station are improving.

2.3 Changes in Vegetation Productivity and Carbon Sequestration Capacity Around Longyangxia Reservoir

Vegetation productivity analysis reveals that GPP and NPP around Longyangxia showed consistent declining trends from 2001-2004 ($P < 0.05$), with rates of -0.04 kg $C \cdot m^{-2} \cdot yr^{-1}$ and -0.093 kg $C \cdot m^{-2} \cdot yr^{-1}$, respectively. This period coincided with the initial reservoir impoundment phase, during which rising water levels submerged grasslands, reducing photosynthesis and vegetation productivity.

From 2005-2021, vegetation NPP and GPP showed slight increasing trends, peaking in 2020 at 0.4 kg $C \cdot m^{-2} \cdot yr^{-1}$ and 0.73 kg $C \cdot m^{-2} \cdot yr^{-1}$, respectively. Net Ecosystem Productivity (NEP) showed a significant increasing trend from 2000-2020 [Figure 9: see original paper] with a rate of 0.003 kg $C \cdot m^{-2} \cdot yr^{-1}$, though still far below the national average of 1.01 kg $C \cdot m^{-2} \cdot yr^{-1}$. The 2000-2004 period represented rapid reservoir area expansion, with water increases submerging vegetation and soil, consequently reducing vegetation productivity (GPP, NPP) while heterotrophic respiration decreased at a slower rate, resulting in negative NEP values. After 2005, as reservoir area growth slowed and stabilized, vegetation photosynthesis and carbon sequestration capacity gradually recovered, though the recovery process remains slow. The shift from carbon source to carbon sink indicates improving vegetation carbon sequestration capacity, particularly after 2005.

2.4 Land Use Changes Around the Hydropower Station

The ecological environment around Longyangxia Hydropower Station is influenced by both climate change and human activities. Under climate warming, vegetation in Northwest China has gradually recovered over recent decades. However, for hydropower stations and their surrounding areas, reservoir impoundment reduces temperature variation amplitude, particularly with greater winter warming, which benefits plant growth. Increased water area enhances underlying surface heat capacity, strengthens atmospheric stratification stability, reduces cloud cover, increases sunshine duration, and raises solar radiation received by plants. Declining relative humidity moderates transpiration, leaving more water available for photosynthesis and plant growth. Overall, reservoir impoundment creates favorable conditions for plant growth, with vegetation improvement rates around Longyangxia exceeding those in other regional areas, suggesting that hydropower construction and operation impacts outweigh climate change effects during the same period. Other human activities such as the Grain for Green program may also contribute, but their impacts would appear as abrupt changes; given the small magnitude of cultivated land and grassland proportion changes, hydropower construction and operation likely dominate ecological environment changes.

Land use analysis reveals that overall patterns remained stable from 2000-2020, with land use types ranked by proportion as: grassland, water bodies, unused land, cultivated land, and forestland. Grassland proportion increased slightly from 42.73% to 45.55%, while cultivated land and water bodies decreased by 1.33% and 1.37%, respectively, with other types showing minimal change. The land use transfer matrix (Table 3) shows significant water area increases of 360.97 km^2, with conversions from grassland, cultivated land, and unused land to water bodies driving reservoir expansion. Most grassland conversion occurred to water bodies and unused land, representing the primary cause of grassland area reduction.

Discussion

All construction and operational projects inevitably impact surrounding vegetation growth, land use, and ecological environments. This remote sensing monitoring study of Longyangxia Hydropower Station’ s ecological impacts in an arid region reveals that construction and operation have generally benefited vegetation growth and wetland area expansion, demonstrating positive ecological benefits. However, hydropower development also affects water quality, fish migration patterns, fish populations, fish mortality, and biodiversity. Future research should incorporate these factors for deeper and more comprehensive assessment of hydropower impacts on surrounding ecological environments.

In buffer zone establishment, the reservoir scope represents annual reservoir boundaries, while total land use area includes both reservoir and peripheral zones, explaining the apparent discrepancy between increasing wetland area and decreasing water body proportion in Table 2. The findings indicate that hydropower construction and operation in arid regions benefit overall ecological environment improvement, providing important support for China’ s energy transition from fossil fuels to clean energy and promoting synergy between rapid economic development and ecological protection.

Conclusions

Using Landsat satellite series data and multiple terrestrial remote sensing products, this study analyzed the impacts of hydropower station construction and operation on surrounding ecological environments in arid regions. The main conclusions are:

1) Longyangxia Hydropower Station' s construction and operation promoted wetland protection, with reservoir area increasing significantly by 5.66 km^2 from 2000-2021.

2) The operational process (impoundment) created favorable conditions for vegetation growth. Over the past two decades, the proportion of high vegetation coverage areas increased, with 60%-80% FVC areas showing the most significant increase at $0.61\% \cdot a^{-1}$. Mean NDVI doubled, indicating improving vegetation growth conditions.

3) Vegetation carbon sequestration capacity improved, particularly after 2005 when the area shifted from carbon source to carbon sink. As reservoir area stabilized, vegetation productivity (GPP, NPP) gradually recovered with non-significant increasing trends.

4) Hydropower construction and operation did not alter the overall land use pattern. From 2000-2020, land use proportions ranked as: grassland, water bodies, unused land, cultivated land, and forestland. Grassland proportion increased slightly, while cultivated land and water bodies decreased marginally, with other types showing minimal change.

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Note: Figure translations are in progress. See original paper for figures.